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UNIVERSITY OF ALBERTA

A Comparison of Spatial and Verbal Working Memory

BY

Karen Z.H. Li

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Master of Science.

DEPARTMENT OF PSYCHOLOGY

Edmonton, Alberta

Fall, 1991

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled A Comparison of Spatial and Verbal Working Memory submitted by Karen Z.H. Li in partial fulfilment of the requirements for the degree of Master of Science.

Allen R. Dobbs

Marcia Spetch

Robert B. Wilberg

Date: Aug. 27/91

Dedication

To my parents, for teaching me to be independent.

Abstract

In Baddeley's (1986) model, working memory (WM) is characterized as a limited capacity system with several components. These components include a central executive (CE) that serves to control, initiate and terminate processing, as well as at least two short term stores, the articulatory loop (for verbal information) and the visuospatial scratch-pad, or VSSP (for visuospatial information). A survey of the WM literature reveals that paradigms devised to assess WM incorporate a mixture of components. Dobbs and Rule (1989) have recently used a WM task that is said to emphasize control of processing while systematically increasing storage demands. A spatial version of the Dobbs-Rule WM task was developed to allow a comparison of CE ability using two modalities. The present research examines whether (1) performance on the Verbal and Spatial WM tasks is similar (2) the two storage components are independent and (3) there is a single controller of processing that is not modality specific. Findings indicate that Spatial and Verbal WM performance was similar. The results of the second and third experiments provide further evidence that both the Spatial and Verbal WM tasks assess the control of processing and require little in the way of storage.

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I wish to thank Dr. Allen Dobbs for his guidance and encouragement during the past two years. I am grateful for the opportunity to have learned about not only the "what" but also the "how-to" aspects of research from him. I am also grateful to Dr. Brendan Rule for her advice and support during the short time that I knew her. I wish to thank Drs. Marcia Spetch, Robert Wilberg, and the members of the Cognitive Seminar group for their helpful comments on the thesis research. Thanks are also due to the psychology graduate students for their advice, moral support and friendship, as well as to Trish Kurylowich and Edna Tepper for their assistance in testing. Finally, special thanks go to Jeff Drugge, whose constant encouragement is both inspiring and essential to me.

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Using Baddeley's (1986) model, working memory (WM) may be defined as the ability to hold items in immediate memory and perform procedural operations at the same time. The model consists of at least three components including a Central Executive (CE) that serves to control, initiate and terminate processing, and two short term stores, the Articulatory Loop and the Visuo-spatial scratch-pad or sketchpad. The two storage components serve to maintain items in WM that are verbal or visuospatial in nature, respectively. Baddeley (1986) suggested that the source of individual variation in WM performance may be due to differences in (1) storage capacity, (2) processing capacity, or (3) CE flexibility, the ability to quickly switch from one procedural operation to another. Although Baddeley advocated the investigation of each source of variation separately, a survey of the WM literature reveals that paradigms devised to assess WM incorporate a mixture of these components.

To address this problem in the WM literature, Dobbs and Rule (1989) used a verbal WM task designed to emphasize CE flexibility while systematically increasing storage demands. For the present research, a spatial analogue of the Dobbs-Rule task was developed to allow a comparison of CE ability in the verbal and spatial modalities. Three experiments were completed to examine whether (1) the two WM tasks are comparable (2) the two storage

components of the WM model are independent of each other in capacity and (3) there is a single controller of processing or separate control components for each modality.

Before describing the three experiments, background information about the WM model will be discussed. This will be followed by a review of the research aimed at testing two central assumptions of the WM model: that the two storage components of the WM system are independent, and that there is one unitary control component.

The WM model

The version of the working memory model that will be used is the most recent tripartite system (Baddeley, 1986) in which there are separate components. It is important to distinguish between this recent formulation and past versions of the WM model (e.g., Baddeley & Hitch, 1974) in which the control of processing and the processing routines themselves were not distinguished. Processing routines include activities such as encoding, outputting, and tagging of items to be remembered. In the most recent model, the CE component serves to initiate, terminate and control the processing routines. Additional functions of the CE, adapted from the Supervisory Attentional System of Norman and Shallice (1986), are the planning of processes, conflict resolution in concurrent processing situations, and

supervision of difficult or novel processing sequences (Baddeley, 1986). Other theorists have ascribed to the CE functions such as decision-making (Logie, 1986) and memory updating (Morris & Jones, 1990).

Storage components of the WM model. Baddeley has posited that the articulatory loop serves to store phonologically coded information, and retains the information through maintenance rehearsal. The visuospatial scratch-pad (VSSP) is the lesser studied of the two storage components (Baddeley, 1986; Logie, 1986; Quinn & Ralston, 1986), and the means by which information is maintained in the VSSP have not been clearly defined (Baddeley, 1986; Frick, 1988). Baddeley's chapter (1986) on the articulatory loop provides a review of the literature associated with that component of WM, so that information will not be repeated here. More relevant is the literature on the contrast between the storage components in the WM model.

One issue that has been investigated is whether the rehearsal mechanism of the VSSP is analogous to that of the articulatory loop. Frick (1988) has offered a theory of representation in the VSSP that is quite different from that of the articulatory loop. He posited that information is stored in the VSSP in an unparsed format, and then is parsed prior to recall. Frick argues that it is the process of parsing at recall that causes capacity limitations, due to a maximum number of items that can be parsed at a given time. Baddeley, in

his chapter on visuo-spatial memory (1986), reviewed some evidence suggesting that the contents of the VSSP may be rehearsed by means of eye movements. However, he concedes that this hypothesis cannot account for the visualization of non-spatial stimuli such as colours, thus concludes that the idea of maintenance rehearsal through eye movements is limited. Beyond these accounts, the issue of representation in the VSSP remains understudied.

Researchers have focused more on the relation of the VSSP to the other WM components. The most frequently used strategy in this area has been to pair a primary task that occupies one of the storage components with concurrent secondary tasks that occupy the same or different components. Selective interference is expected such that there is more task interference when the primary and secondary tasks are alike in modality than when they differ. This type of result has been taken as evidence for the independence of the two storage components of WM. The selective interference is assumed to result from competition for capacity within one storage component (the modality-match condition), as compared to little competition for capacity when the items to be remembered occupy different storage components (the modality-mismatch condition).

Studies in the area of visuospatial memory have often employed visual imaging tasks, such as list learning using a peg-word mnemonic (e.g.,

Baddeley, Grant, Wight, & Thomson, 1973; Baddeley & Lieberman, 1980; Logie, 1986), or spatial reasoning (e.g., Brooks, 1968; Farmer, Berman & Fletcher, 1986; Salthouse, Mitchell, Skovronek, & Babcock, 1989), as primary tasks in dual task situations. Other visuospatial tasks have also been used in concurrent task paradigms (e.g., Baddeley & Lieberman, 1980; Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986; Morris, 1989; Smyth & Pendleton, 1989) in which the general finding is that visuospatial tasks interfere with other visuospatial tasks, but not with verbal tasks, thus supporting the hypothesis of independent storage components.

Another related issue in the spatial WM literature involves identifying the part of the WM system responsible for individual differences in spatial WM ability. Salthouse and colleagues (Salthouse, Babcock, Mitchell, Palmon, & Skovronek, 1990) recently investigated the source of individual differences in visualization ability by comparing groups of subjects identified as high and low visualizers, based on four psychometric tasks. Using a battery of experimental tasks, these researchers found no support for the hypotheses that individual differences are due to variation in the speed of processing, or variation in the ability to retain spatial information. Nor did they find support for the hypothesis that individual differences lie in the ability to simultaneously process information while storing the products of the intermediate processing

steps. Based on their results, these authors offered a fourth hypothesis, that individual differences may be attributed to tradeoffs such that poor visualizers are unable to store as much information because they require more overall capacity for processing.

To summarize the spatial WM literature, the term spatial WM has been used to loosely categorize a variety of tasks requiring the simultaneous retention and manipulation of visuospatial information. The majority of spatial WM studies have yielded support for the notion of separate memory stores for verbal and visuospatial information. However, a finer breakdown of task components is needed to more fully understand the source of individual variation in these spatial WM tasks. Salthouse et al. (1990) attempted to identify the source of individual differences in visualization ability, one aspect of spatial WM, but did not provide very satisfactory conclusions.

A focus on the CE. To date, little research exists that has attempted to investigate the specific functions of the CE. Baddeley (1986) in fact referred to the research on the CE as an "area of residual ignorance" (p.225).

Daneman and Tardif (1987) addressed the issue of whether Baddeley's (1986) conceptualization of a singular CE component is valid, or whether each processing domain has its own limited capacity processor. These authors contrasted processing-only and processing-plus-storage tasks in three

processing domains: visuospatial, verbal, and arithmetic. They argued for the case of separate processors rather than a central one, based on low correlations among the processing tasks. However, their spatial processing-plus-storage scores had little variability and were close to ceiling, so their conclusions are questionable.

Phillips and Christie (1977) provided evidence for a single CE component in WM by contrasting two secondary tasks, one requiring the addition of digits (high processing requirements) and another requiring reading the digits out loud (low processing requirements). These two tasks did not overlap in modality with the primary task, however interference was found when processing was required in the secondary task, but not when the secondary task required minimal processing. Based on these results, the authors argued that the interference was due to competition in a unitary CE component rather than competition for capacity within one of the storage components.

More recently, Babcock and Salthouse (1990, expt. 1) presented evidence for a single controller of processing that is not modality specific. Similar to Daneman and Tardif (1987), these authors contrasted tasks requiring storage-only and processing-plus-storage in the verbal and spatial modalities. They found that the correlation between the two storage-only tasks was not

significant but the correlation between the two processing-plus-storage tasks with storage-only partialled out was significant.

Babcock and Salthouse interpreted this pattern of results as evidence for a common CE component and unrelated storage components. They also suggested that the source of individual differences in WM ability may be found within storage or CE components. Their research strategy is notable because of its similarity to that used in Experiment 1 of the present research. However, it is also important to note that Babcock and Salthouse did not distinguish between the control of processing routines (i.e., activation, termination, scheduling of processing) and the processes themselves. Salthouse and colleagues (Salthouse et al., 1990) have in fact suggested that the source of individual differences in spatial WM may be likened to a "desk-top" metaphor such that poor visualizers require more "work-space" for processing and consequently leave less "work-space" for short term storage.

Baddeley's (1986) chapter on the CE provides a theoretical framework for this component of WM but does not provide many suggestions of paradigms for its study. He emphasized the need to distinguish between two aspects of executive function: overall processing capacity and flexibility (Baddeley, 1986). Flexibility can be thought of as the ability to shift rapidly between different processing routines, whereas overall processing capacity may

be defined as the number of processing "jobs" that can be done at one time.

Baddeley (1986) suggests that the cause of differences in CE ability may be due to differences in (1) flexibility, a CE function, or (2) the efficiency of processing routines, something that is arguably independent of CE functioning. He concluded that there is a need for ways of independently assessing each of the proposed reasons for differences in CE function. The distinction between processing and the control of processing has been largely ignored in the WM literature, but is important for the research to be reported.

The CE and mental agility. Dobbs and Rule (1989) developed a task to study the flexibility, or "agility" of the CE while attenuating storage and processing demands. Their task requires subjects to listen to digits presented auditorially and repeat the digits heard as they are being presented. The processing requirements are minimized in this task because each one of the procedural operations that must be coordinated (e.g., encoding, storing, retrieving) is relatively simple and arguably well integrated for verbal materials such as single digits. The storage demands of the task are gradually increased by one item in each of the Lag conditions.

In the Lag 0 condition, subjects repeat the digits immediately after each item is presented. In this condition, each item must be remembered for a trivial amount of time before it is used as a response and then dropped from

memory. In the Lag 1 condition, subjects echo the digit sequence with a one item delay such that when they hear a digit (e.g., item # 6), the correct response is to say the digit presented one previous in the sequence (e.g., item # 5) each time. In this condition, one additional item must be stored before it is used as a response. In subsequent Lag conditions (Lags 2, 3, 4, etc.), the Lag number indicates the number of items behind in the sequence that the subject must be when repeating the sequence. Therefore, as Lag number increases each time, the number of items to be remembered increases by one.

Dobbs and Rule (1989) concluded that when subjects track numbers one item back, their WM task requires repetitive shifts in processing but minimal storage in the articulatory loop. When subjects track numbers two items back, storage demands increase because more items must be maintained until they are verbalized at the appropriate time. Their conclusions were supported by a pattern of results in which the strength of correlations between Digit Span Forward (a measure of verbal storage ability) and their WM task increased with Lag number.

In recent parametric investigations, this WM task (Schwartzberg, Dobbs, & Rule, 1991) has shown similar performance functions using either digits, letters, short words or long words, as the items. In addition, varying the time interval between stimulus onsets has yielded no effects on

performance.

Aside from a small number of studies (Babcock & Salthouse, 1990; Daneman & Tardif, 1987; Phillips & Christie, 1977), few researchers have attempted to specify the proportionate involvement of CE and storage functions in their WM paradigms. Even fewer researchers have attempted to separate processing and the control of processing experimentally.

Dobbs and Rule (1989) attempted to separate these two aspects of the CE with their verbal WM task. Because of this feature, their task was used in the present research, and a spatial analogue was developed to allow a comparison of verbal and spatial WM with an emphasis on CE flexibility.

Experiment 1

The goal of the first experiment was to determine whether the Spatial WM task developed would result in the same functional characteristics as have already been found with the traditional Dobbs-Rule WM task (Dobbs & Rule, 1989). Spatial WM, verbal WM, Spatial Span, and Verbal Span tasks were contrasted in a manner similar to that used by Babcock and Salthouse (1990). However, rather than using processing-plus-storage tasks as those authors did, the present experiment used spatial and verbal tasks emphasizing the control of processing. These tasks will be referred to as the Spatial and Verbal WM tasks for the sake of brevity.

Because Dobbs & Rule (1989) found that the correlation between performance on the Digit Span Forward and the Verbal WM task increased with Lag number, it was expected that a similar result would be found here, and that the correlation between spatial span performance and Spatial WM performance would increase in the same way. In addition, a version of the spatial WM and span tasks were given in which location cues did not remain on the screen. This was done as an exploratory component of the study, to determine whether performance functions differ substantially from those of the aforementioned tasks.

Method

Subjects

Forty-three undergraduate students, 19 females and 24 males, from the Psychology department at the University of Alberta participated in the experiment as an option for course credit (M age = 19.30, SD = 1.94). Data for participants who had experienced a head injury in the past year, who were older than 35 years, or for whom English was not their first language, were excluded from the analyses.

Equipment

All three experiments used the same equipment. The visual stimuli were presented on a Zenith model 1490 VGA monitor. Attached to the

monitor was a Carrol Smart-Frame that read the x-y coordinates of the touch responses on the screen. The monitor was tilted at a 30 degree angle from the horizontal to minimize fatigue (Baddeley et al., 1986). The Verbal WM stimuli were presented through headphones from audiotape.

Design and procedures

A within subjects design was used in which subjects completed the three versions of the WM task and the three corresponding memory span tasks. Analogous to the WM tasks, the three types of span measures were a digit span forward, presented auditorially by the experimenter, and the two versions of a spatial span, presented on the computer screen. The order of the tasks was counterbalanced.

Digit Span Forward. Standard procedures for the digit span task were used (e.g., Wechsler, 1944), in which the experimenter presented sequences of single digits beginning with a span length of four. Subjects repeated the sequences immediately after they were presented and the experimenter indicated that they were to begin. Upon correct completion of a trial, subjects were presented with a sequence that was one item greater in length. If an error was made, another trial of the same span length was presented. The task was terminated after two consecutive incorrect trials at the same span length.

Spatial Span. The spatial span task was similar to the Corsi block span

task, but was adapted for presentation on a computer monitor. As in a study by Owen and colleagues (Owen, Downes, Sahakian, Polkey, & Robins, 1990), nine open squares (approx. 4.0 x 4.0 cm) were arranged non-systematically on the computer screen. A span sequence was indicated by the consecutive presentation of a large "X" inside the squares. The duration of each "X" was 250 ms, with an ISI of 1.8 s, in order to approximate the rates of stimulus presentation in both the Dobbs-Rule WM task (Dobbs & Rule, 1989), and the Corsi block span test (e.g., De Renzi, Faglioni, & Previdi, 1977). Figure 1 shows an example of the visual display.

Subjects observed a sequence of four "Xs", each presented in one of the squares, and were signalled to touch the squares in the same order when the word "RECALL" was shown in the upper left hand corner of the screen. After each successful trial, the sequence length increased by one item. A trial of the same length was repeated if the subject made an error. The dependent measure used was the highest span length correctly completed before the subject made two consecutive errors at the same span length.

Spatial non-target Span. In the non-target version of the spatial span task, the procedures were similar to those of the Spatial span. However, instead of the open squares remaining on the screen to serve as location cues and "Xs" appearing inside each square, green dots (approximately 1 cm in

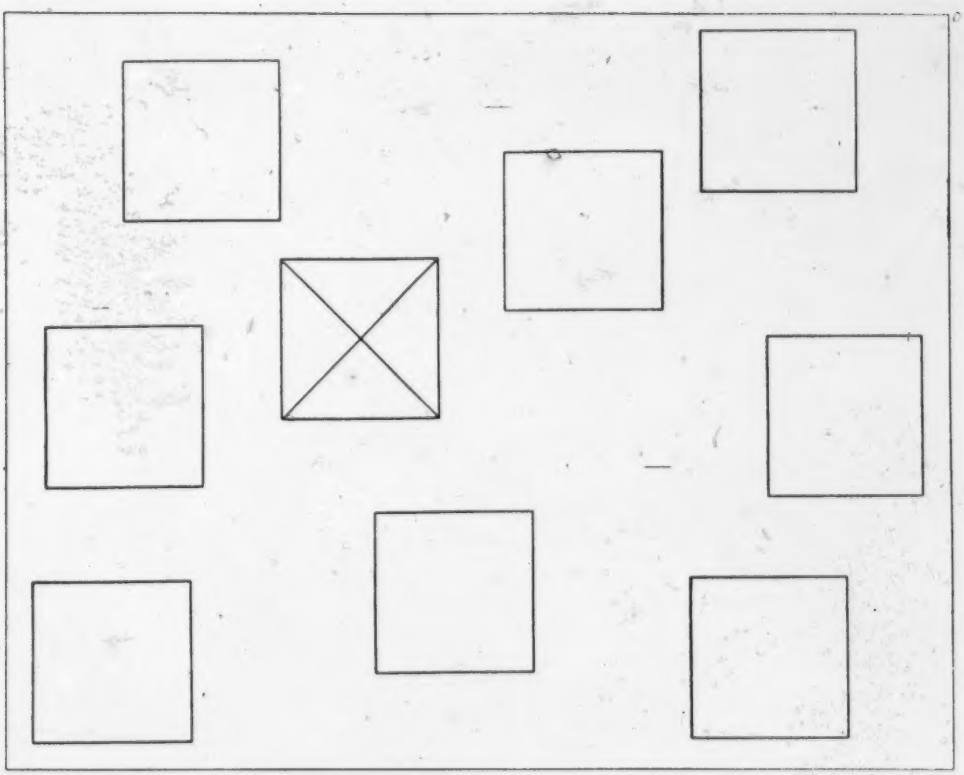

Figure 1. Visual Display for Spatial WM Task.

diameter) appeared on a blank screen at the same time intervals as the "Xs" in the Spatial Span task. The distance between the touch response and the appropriate target position (in pixel units) was recorded. For comparison with the other spatial tasks, "correct" and "incorrect" responses were recorded using the same criterion target region (approx. 5.2 x 5.2 cm, or 130 x 130 pixel units) around the targets as in the Spatial Span task.

Verbal WM task. Sequences of single digits were presented on audiotape through headphones at a rate of one digit every 1.8 s. In the Lag 0 condition, subjects were to say each digit immediately after it was presented. In the Lag 1 condition, subjects echoed the sequence as in Lag 0, but were one item behind in the sequence. In the Lag 2 condition, the numbers were repeated two items behind in the sequence; in the Lag 3 condition, the numbers were repeated three items behind, and so on, up to Lag 5, in which the numbers were repeated five items behind in the sequence.

Two trials were completed in each Lag condition and the best score out of two trials was used for analyses. This particular measure was used for analyses primarily because of the nature of the task. It was felt that trials in which there were lapses in attention or confusion about when to begin responding would not reflect true ability, and so the best score out of two trials was used rather than an average of scores.

In each trial, the sequences were long enough so that a maximum of ten correct responses was possible (see Dobbs & Rule, 1989). The dependent measure used was the number of items correct to the first error in each trial.

Spatial WM task. In the Spatial WM task, the stimuli were the same as in the Spatial Span task. Subjects viewed the same array of nine open squares and "Xs" were presented at the same stimulus duration and ISI as in the Spatial Span task. In the Lag 0 condition, subjects repeated the sequence of "Xs" by touching the square in which an "X" was just presented immediately after the presentation of each item. In the Lag 1 condition, subjects touched the square in which an "X" had appeared one item previous in the sequence. As in the Verbal WM task, subjects progressed from Lag 0 to Lag 5, completing two trials in each condition. For each trial, the dependent measure was the number of correct responses to the first error, with a maximum of ten correct responses. For each Lag, the best score out of two trials was used for analyses.

Spatial non-target WM task. The Spatial non-target WM task was the same as the Spatial WM task above, but the screen remained blank and green dots were presented instead of "Xs". As in the Spatial non-target span task, correct responses were scored using a criterion target region (approx. 5.2 x 5.2 cm, or 130 x 130 pixel units) around the targets. The distance of the

touch responses from the corresponding targets was also recorded (see Appendix 1 for experiment briefing and task instructions).

Results

Figure 2 shows the results of the three WM tasks for each Lag condition.

Spatial and Verbal WM tasks

To determine whether performance was influenced by stimulus modality, lag condition, or an interaction of both factors, a 2 (m/f) x 2 (Spatial or Verbal WM task) x 4 (Lags 2-5) MANOVA was done with Sex as a between Ss variable and Task and Lag as within Ss variables. Data from Lags 0 and 1 were excluded from these analyses because of the low variability and probable ceiling effects in these conditions.

A main effect of Lag was found, $F(3,39) = 37.38$, $p < 0.001$. Means for Lags 2-5 are 8.56, 7.35, 5.90, and 4.84, respectively. Newman Keuls analysis revealed that performance on all four lags were significantly different from each other ($p < 0.05$). The Sex x Task interaction was also reliable, $F(1,41) = 4.50$, $p < 0.040$. However, subsequent Newman Keuls analyses indicated that no means for this interaction were significantly different at an alpha of 0.05. Means for the Spatial WM task were 6.13 (m) and 6.71 (f); for the Verbal WM task they were 7.32 (m) and 6.51 (f).

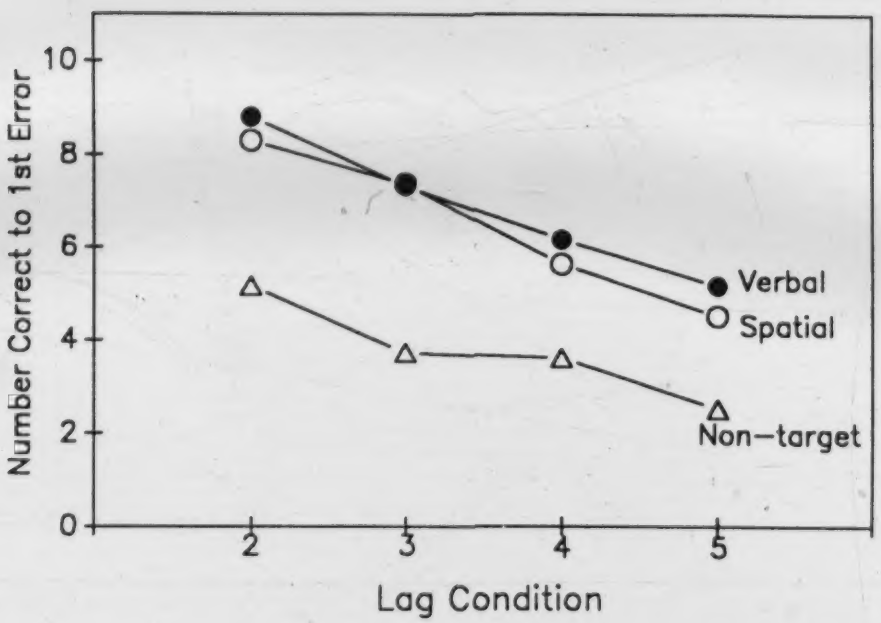

Figure 2. Performance on Three WM Tasks by Lag.

Span tasks

To determine whether there were differences in storage capacity depending on modality, a two-way ANOVA was done using Sex (m/f) as a between Ss variable and Modality (Spatial, Verbal, and Spatial non-target Spans). The main effect of Modality was reliable, $F(2,40) = 92.77$, $p < 0.001$. Newman Keuls comparisons revealed that all three tasks were reliably different ($p < 0.05$). Figure 3 shows mean performance for each of the span tasks.

Spatial and Spatial non-target WM tasks

To investigate the possible differences between the two spatial WM tasks, Spatial and Non-target WM data were analyzed in a 2 (m/f) x 2 (Spatial / Non-target WM task) x 4 (Lags 2-5) MANOVA, using Sex as a between Ss variable, and Task and Lag as within Ss variables. Main effects of Task, $F(1,41) = 50.29$, $p < 0.001$, and Lag, $F(3,39) = 28.39$, $p < 0.001$, were reliable. Mean scores were 6.45 and 3.75 for the Spatial and Spatial non-target tasks respectively. Mean scores were 6.73, 5.55, 4.62, and 3.51 for Lags 2-5, respectively.

The Task x Lag interaction also proved reliable, $F(3,39) = 3.79$, $p < 0.018$. Newman Keuls analyses revealed that Lag 2 differed from Lags 3 and 4, Lag 5 differed from Lags 3 and 4, and that Lag 2 differed from Lag 5 ($p <$

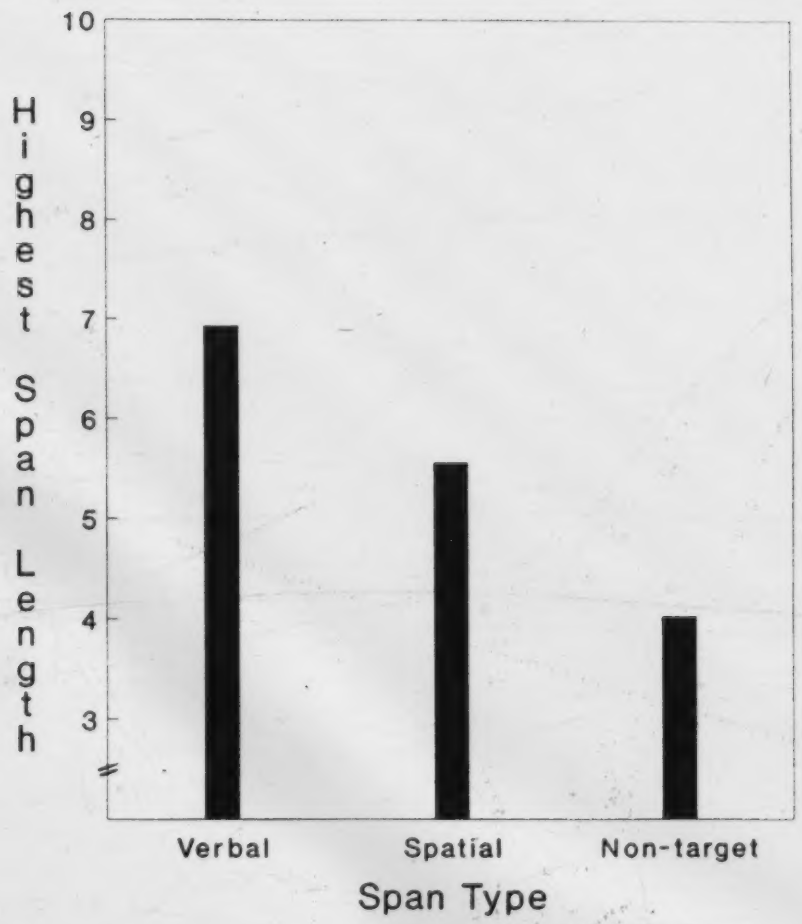

Figure 3. Memory Span Performance.

0.05). It was also found that Spatial WM performance at Lags 2 and 3 was greater than performance at the other Lag conditions in both the Spatial and Non-target tasks ($p < 0.01$), but did not differ from each other (see Fig. 2).

Spatial non-target WM error data

Analyses of the error data were performed for the non-target version of the Spatial WM task to determine how the spatial accuracy of responses was affected by the retention interval required and the ordinal position of the items. The distance between touch responses and centre of each corresponding target was calculated by the program in pixel units.

A repeated measures ANOVA was performed using Lag (0-5) and Serial Position (item 1, 4, 7, 10) as within Ss measures. Only four serial positions were used in the analysis to reduce its size. Lags 0 and 1 were included in this set of analyses because the variability in these conditions was sufficient, in contrast to the accuracy data analyses reported above.

Main effects of Lag, $F(5,37) = 140.05$, $p < 0.001$, and Serial Position, $F(3,39) = 76.72$ $p < 0.001$, were found. The Lag x Serial Position interaction was also reliable, $F(15,27) = 22.86$, $p < 0.001$. Mean scores at Lags 0-5 were 23.28, 45.83, 93.84, 134.45, 155.17, and 179.50, respectively. Mean scores collapsed across Lag were 59.87, 87.37, 126.81, and 147.32 for serial positions 1, 4, 7, and 10, respectively.

Newman Keuls analyses indicate that the distance error was greater at Lags 5, 4, and 3 than it was at Lag 2, and that error at Lags 1 and 0 was significantly smaller than at the other lags ($p < 0.05$). It was also found that error at Serial position 10 and 7 was greater than at position 4, which was greater than at position 1 ($p < 0.05$). Furthermore, error at positions 7 and 10 at Lag 5, and position 10 at Lags 4 and 3 were significantly greater than at the other lag conditions and serial positions. Figure 4 illustrates the mean error in pixel units for Lags 0-5 at all serial positions.

Relations among measures

Both Digit and Spatial Span are considered to be measures of the storage capacity of short term memory. Regression analyses were performed to determine the extent to which performance on the span tasks account for the variability in each of the Lag conditions of the WM tasks.

Stepwise regression was done for each of the WM measures (Lags 2-5 for Spatial and Verbal WM tasks) using Sex, Spatial Span, and Digit Span as predictor variables. It was expected that the span variables would be more predictive of WM performance at the higher Lag conditions.

Few significant results emerged from the analyses, using an alpha to enter of 0.05. No significant predictors emerged when Spatial WM measures were used as criterion variables. However, in the Verbal WM data, Sex was a

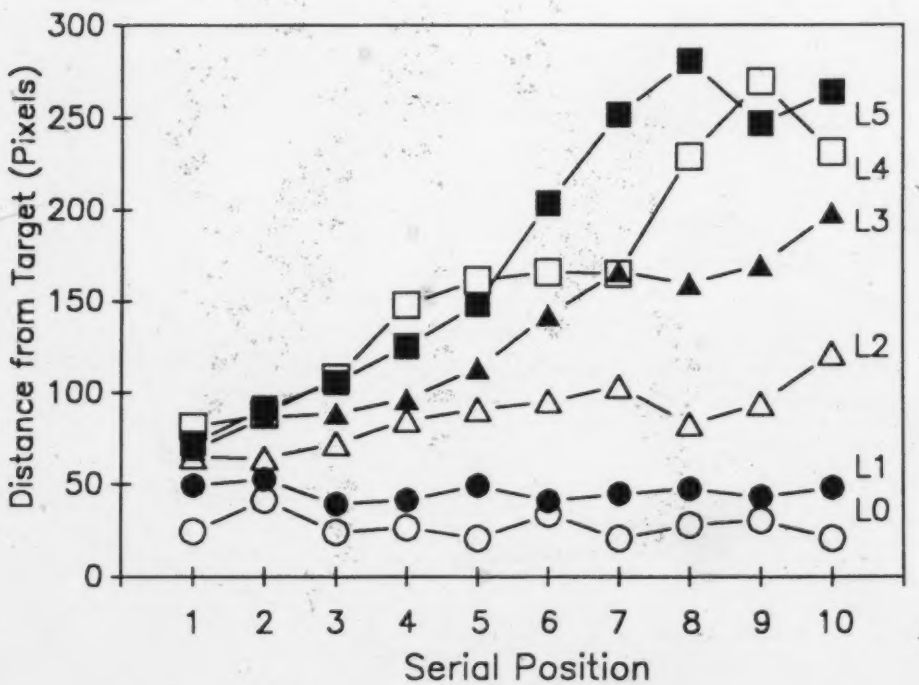

Figure 4. Mean Errors on Spatial Non-target WM Task: Lags 0-5.

significant predictor of WM performance at Lag 2 ($\underline{B}$ = -0.316, $\underline{R}^2$ = 0.10, $\underline{p}$ < 0.039). At Lag 4, Spatial Span entered as significant ($\underline{B}$ = 0.338, $\underline{R}^2$ = 0.11, $\underline{p}$ < 0.027), followed by Digit Span Forward ($\underline{B}$ = 0.295, $\underline{R}^2$ change = 0.09, $\underline{p}$ < 0.011). Table 1 shows the intercorrelations among span and WM variables.

Discussion

The primary question to be answered in this experiment was whether the Spatial WM task that was developed assesses the same thing as the Verbal WM task, but in the spatial modality. The lack of a Task main effect in the first set of analyses suggests that there is little difference in WM performance across modalities. Assuming that the WM paradigm does indeed assess CE capacity (Dobbs & Rule, 1989), the results from this analysis support the notion that the CE is unitary, and not modality specific.

Further support for the assumption that the WM paradigm assesses CE functioning in both spatial and verbal modalities, comes from considering span performance across tasks. The analysis of span measures indicates the best performance on the Digit Span, poorer performance on the Spatial Span, and poorest performance on the Spatial non-target Span. It is interesting to note that the span results are consistent with other published findings (Corkin, 1982; Owen et al., 1990). Assuming that the Digit and Spatial Spans indeed

Table 1
Pearson R Correlations Among WM and Span Measures

	Span	
WM Lag	Spatial	Digit
	Spatial WM	
0	-0.237	0.023
1	0.047	0.053
2	-0.148	0.011
3	0.133	0.140
4	0.218	0.070
5	0.016	0.217
	Verbal WM	
0	--	--
1	0.080	-0.222
2	0.252	0.092
3	0.140	0.036
4	0.338 **	0.297 *
5	0.038	0.045

	Digit Span
Spatial Span	0.008

* $p < 0.05$
** $p < 0.01$

measure the storage capacity in WM, the differences in spatial and verbal storage ability do not correspond with differences in spatial and verbal WM performance. Visual inspection of the performance functions for the two WM tasks indicates that the separation between tasks only begins to occur at Lag 4 (see Figure 2), but is in the direction expected in view of the span data. Possibly the reason for this lack of a Task effect between the Spatial and Verbal WM tasks is that the Lag conditions are almost all sub-span.

The relationship among WM and span measures was assessed through stepwise regression analyses. The results were not overwhelming in providing support for the hypothesis that storage demands increase with Lag number. The results of the Verbal WM task at Lag 4 support this notion, but only weakly. These results are not entirely consistent with previously published findings (Dobbs & Rule, 1989) in that correlations between span and WM measures did not increase substantially with higher Lag conditions in the present research. However, one reason for this discrepancy between studies may be that a much larger age range was used in previously published work (Dobbs & Rule, 1989), allowing for greater variability on each measure.

The finding that Sex was a significant predictor of Verbal WM performance at Lag 2 is partially supported by the Sex x Task interaction found in the analysis of the Spatial and Verbal WM tasks. It is surprising,

however, that the direction of the effects is such that males have higher overall scores on the Verbal WM task than on the Spatial WM task, given the literature on sex differences in verbal and spatial tasks (e.g., De Renzi, 1982).

The Spatial non-target WM task was included as an exploratory measure to see whether there was a difference in processing when the target squares were removed from the display. The Spatial and Spatial non-target WM task analysis indicates that there are definite differences in the two versions of the touch-screen WM task, but the functions remain relatively parallel. The analysis resulted in a moderate Task x Lag interaction; however, the two performance functions *converge* rather than diverge as Lag number increases (see Figure 2). A floor effect may account for the slight convergence at the higher lag conditions. It may not be the case that the Non-target version of the task requires storage of material that is different from that required in the Spatial WM task. Rather, the pattern of results suggest that Non-target WM performance was poorer because the precision of the spatial memory required in the non-target version is greater than that in the target-present condition. Analysis of the error data on the Spatial non-target WM task suggests that memory for spatial locations deteriorates as the retention interval increases. The effect of Serial Position suggests that the memory trace for spatial location also degrades within each trial, as if proactive

interference increases as more items have been encoded. A similar pattern of results was found in previous work (Gabriele & Wilberg, 1989; Wilberg, 1987).

Strong effects of Lag were found in this experiment as in previous work (Dobbs & Rule, 1989; Schwartzberg, Dobbs & Rule, 1991) such that WM performance decreased monotonically with increasing Lag. A few interpretations of this effect are possible. As Lag number increases, each item must be retained for longer before being outputted and discarded from the memory buffer, possibly resulting in a decrease of fidelity of the memory trace for each item. Another possible explanation of the Lag effect is that as the number of items to be retained in the memory buffer increases, there is an increase in probability of confusion due to proactive interference.

It is also possible that the source of the Lag effect is at the level of processing or control of processing. It has been hypothesized that the control requirements remain the same across Lag conditions (Dobbs & Rule, 1989). Each item presented must be encoded, some aspect of the ordinal position of the item must be tagged, the sequence of items to be remembered must be shifted, and the correct item outputted. However, it is possible that although the control demands remain constant across Lags, the processing routines change slightly. For example, the number of tags to be assigned may increase

across lag conditions, consequently occupying more processing time as Lag increases. The increase in processing time necessary at higher lags may interfere to such an extent that all of the processing routines cannot be completed within the time parameters of the task, thus causing a breakdown in performance.

Experiment 2

The findings of the first experiment suggest that the Spatial and Verbal WM tasks result in similar performance as measured by the criteria used. The following two experiments were designed to study the underlying components of these WM tasks using the concurrent task approach (e.g., Baddeley & Lieberman, 1980; Baddeley et al., 1986; Farmer, Berman & Fletcher, 1986). In Experiment 2, the Verbal and Spatial WM tasks were used as primary tasks, and the secondary tasks were designed to assess memory storage ability, requiring the delayed recall of either verbal or visuospatial information.

The purpose of using such secondary tasks was to determine whether a concurrent memory load in one modality would selectively interfere with performance on the WM task of the same modality. Such a result would provide evidence for the assumption that the two storage components of WM are independent in capacity.

Method

Subjects

Forty-seven undergraduates, 21 females and 26 males, from the University of Alberta participated in the experiment as an option for course credit (M age = 21.00, SD = 3.67). Data for participants who had experienced a head injury in the past year, who were older than 35, or for whom English was not their first language, were excluded from the analyses.

Design and procedures

A within-subjects design was used in which subjects completed a total of six conditions. The spatial and verbal secondary tasks were completely crossed with the Spatial and Verbal WM tasks and the WM tasks were also given alone as single-task control conditions. Order of tasks was counterbalanced.

WM tasks. The same Spatial and Verbal WM tasks as in Experiment 1 were administered with two trials each at Lags 2, 3, and 4. Based on the results of Experiment 1, Lags 0 and 1 were omitted because ceiling effects were found, and Lag 5 was omitted because of floor effects. For each trial, the dependent measure was the number of correct responses to the first error, with a maximum of ten correct responses. For each lag, the best score out of two trials was used for analyses.

Verbal load task. In the verbal load conditions, the experimenter verbally presented three pronounceable non-words to remember before each WM trial and asked the subject to recall the non-words in the correct order after the WM trial. The non-words were chosen from a list of paralogs (CVCVC strings) normed on their similarity to real words (Taylor, 1959). Appendix 2 lists the paralogs used and the frequency with which they were associated with a common word (M frequency of association was 14.0 out of 102 responses). One point was given for correct pronunciation of each word, and a fourth point was given for indicating the correct order. The score out of four points was recorded for each group of three non-words.

Spatial load task. In the spatial load conditions the experimenter showed a series of three circles (approximately 1 cm in diameter) drawn in different positions on three separate pages (8.5" x 11"). Each page was shown for approximately two seconds, and then subjects proceeded to complete a trial of the WM task. After each WM trial, subjects were asked to mark with a small "X" the location of the circles on a blank sheet of paper (8.5" x 11") as accurately as possible and to indicate the order of presentation by labelling each "X" either "A","B", or "C". Subjects were told that they would be scored on accuracy (one point per dot) and order (one point).

In order to control for differential emphasis on primary vs. secondary

tasks in the dual task conditions, subjects were instructed to make sure that they do their best on the memory load component while performing the WM component as points were to be allotted for the number of items that they could recall (see Appendix 3 for briefing and task instructions).

Results

The main question to be answered by the analyses is whether the memory loads interfered with WM performance differentially depending on match of stimulus modality for the concurrent tasks. The prediction was that Verbal Load would interfere more with Verbal WM performance, and Spatial Load would interfere more with Spatial WM performance.

Spatial and Verbal WM alone conditions

To determine whether performance on the WM tasks alone replicated the results of Experiment 1, a 2 (m/f) x 2 (Spatial / Verbal WM task) x 3 (Lags 2-4) MANOVA was performed, using Sex as a between Ss variable, and Task and Lag as within Ss variables. Main effects of Task, $F(1,45) = 4.36$, $p < 0.042$, and Lag, $F(2,44) = 12.88$, $p < 0.001$, were reliable. Mean performance scores on the Spatial and Verbal WM alone conditions were 6.88 and 7.80, respectively. Mean scores collapsed across Task were 8.85, 7.10, and 5.92 for Lags 2-4, respectively. Newman Keuls analyses indicate that the Spatial and Verbal WM means were not significantly different at an alpha of

0.05, and that mean scores at all three Lag conditions were significantly different ($p < 0.05$).

Spatial and Verbal WM difference scores combined

Of primary interest in this experiment is whether dual task interference was greater when task modalities were matched. To assess this hypothesis, difference scores from both Spatial and Verbal WM tasks were used in a 2 (m/f) x 2 (modality matched / mismatched) x 2 (WM modality) x 3 (Lags 2-4) MANOVA, with Sex as a between Ss variable, and Match, Modality, and Lag as within Ss variables. A reliable effect of Modality was found, $F(2,45) = 3.80$, $p < 0.030$, such that interference was greater in the Verbal WM data than in the Spatial WM data. Mean difference scores for the Spatial and Verbal WM conditions were 0.65 and -0.16, respectively. Newman Keuls analysis revealed that there were no significant differences in scores between WM modality.

Subsequent analyses were performed to investigate each of the two WM tasks and secondary task performance individually.

Verbal WM conditions

To determine whether interference effects occurred within the Verbal WM task conditions, a 2 (m/f) x 3 (VWM alone, VWM-verbal load, VWM-spatial load) x 3 (Lags 2, 3, 4) MANOVA was done with Sex as a between Ss

variable, and Condition and Lag as within Ss variables. The main effect of Lag was significant, $F(2,44) = 18.24$, $p < 0.001$. Mean scores collapsed across Condition were 8.75, 7.56, and 6.45 for Lags 2-4, respectively. Newman Keuls analysis revealed that Lags 2, 3, and 4 were all reliably different ($p < 0.05$) when collapsed across Condition. Although the effect of Condition was not reliable, visual inspection of the three functions indicates that overall performance was best in the Verbal WM alone condition, and worst in the VWM-verbal load condition. Figure 5 shows Verbal WM performance in the alone, spatial and verbal load conditions.

To assess dual task decrements on a per-subject basis, a similar analysis was performed using difference scores (dual task scores - single task scores) for each subject. A 2 (m/f) x 2 (modality match / mismatch) x 3 (Lag 2-4) MANOVA was done using Sex as a between Ss variable and Match and Lag as within Ss variables. Only a marginal effect of Match, $F(1,45) = 3.38$, $p < 0.073$, was found. Means difference scores for the match and mismatch conditions were -0.454 and 0.135, respectively.

Spatial WM conditions

To determine whether interference effects occurred within the Spatial WM task conditions, a 2 (m/f) x 3 (SWM alone, SWM-verbal load, SWM-spatial load) x 3 (Lags 2-4) MANOVA was done using Sex as a between Ss

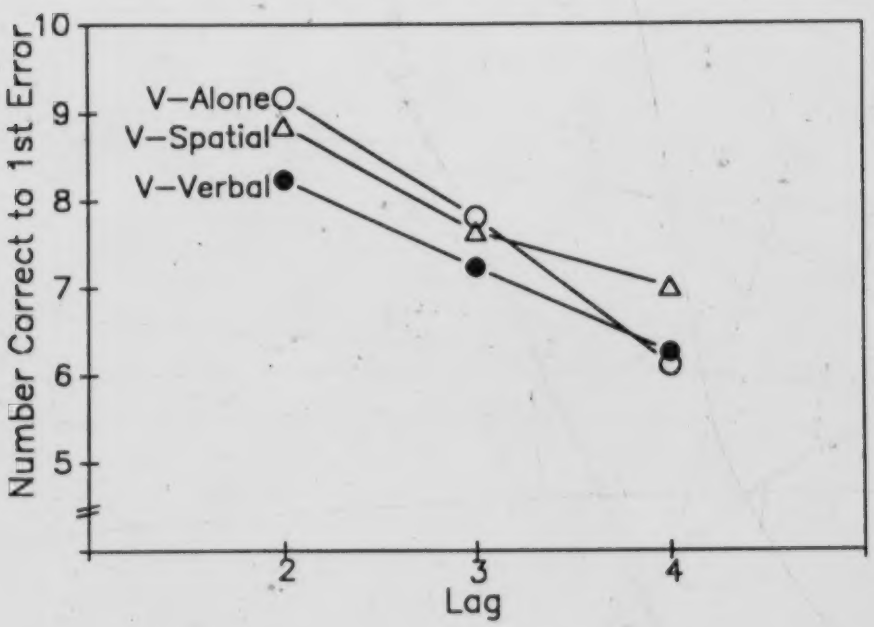

Figure 5. Expt. 2 Verbal WM Task: Alone, With Spatial and Verbal Load.

variable and Condition and Lag as within Ss variables. A main effect of Lag, $F(2,44) = 30.99$, $p < 0.001$, was reliable. Mean scores collapsed across Condition were 8.93, 6.92, and 6.10 at Lags 2-4, respectively. Newman Keuls analysis revealed that Lag 2 was significantly greater than Lags 3 and 4 ($p < 0.05$). The main effect of Condition was not reliable. It is interesting, however, that the direction of the effect is opposite to what was expected: performance in the SWM-spatial load condition was slightly better than in the SWM-verbal load condition, which was slightly better than single task performance. Figure 6 shows mean performance for the Spatial WM conditions as a function of Lag condition.

Difference scores (dual task scores - single task scores) for each subject were also used here to assess dual task decrements on a per subject basis. A 2 (m/f) x 2 (modality match / mismatch) x 3 (Lag 2-4) MANOVA was done using Sex as a between Ss variable and Match and Lag as within Ss variables. No reliable effects were found in this analysis.

Secondary task data

Summary scores were calculated for the secondary task measures by taking the total number of points (maximum = 24) in each condition. To determine whether secondary task performance was affected by the modality of the memory load items, a 2 (spatial / verbal load) x 2 (modality matched /

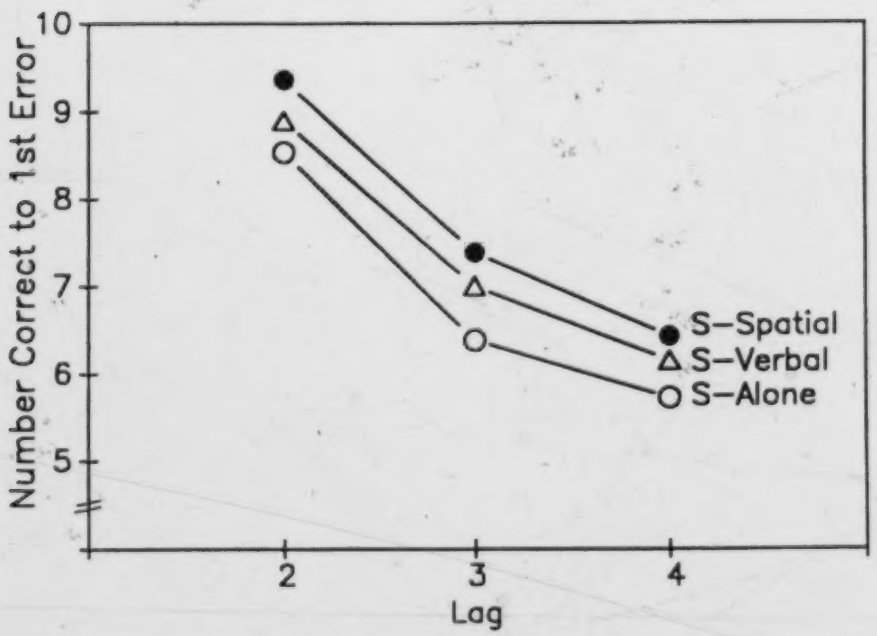

Figure 6. Expt. 2 Spatial WM Task: Alone, With Spatial and Verbal Load.

mismatched) ANOVA was done, using Modality of secondary task and Match in modality as within Ss variables. A main effect of Match, $F(1,46) = 12.85$, $p < 0.001$, but not Modality, was reliable, indicating that the two tasks were not significantly different in level of difficulty when collapsed across WM condition, but that when primary and secondary task modalities were matched, performance on the secondary tasks was poorer than when primary and secondary task modalities were mismatched. Mean scores collapsed across Lag were 19.37 and 20.80 for the matched and mismatched conditions, respectively.

The Modality x Match interaction was also reliable, $F(1,46) = 31.05$, $p < 0.001$. Newman Keuls analysis indicates that secondary task performance in the SWM-verbal load condition was significantly greater than that of the other dual task conditions ($p < 0.01$). Figure 7 illustrates the mean performance on each of the secondary tasks collapsed across Lag.

To determine whether secondary task performance overall was affected by the type of WM task paired with the secondary tasks, a similar MANOVA was done using Modality of WM task (Spatial WM / Verbal WM) and Match (match with WM modality) as within Ss variables. Main effects of Modality, $F(1,46) = 31.05$, $p < 0.001$, and Match, $F(1,46) = 12.85$, $p < 0.001$, were found, indicating that secondary task performance was better when paired

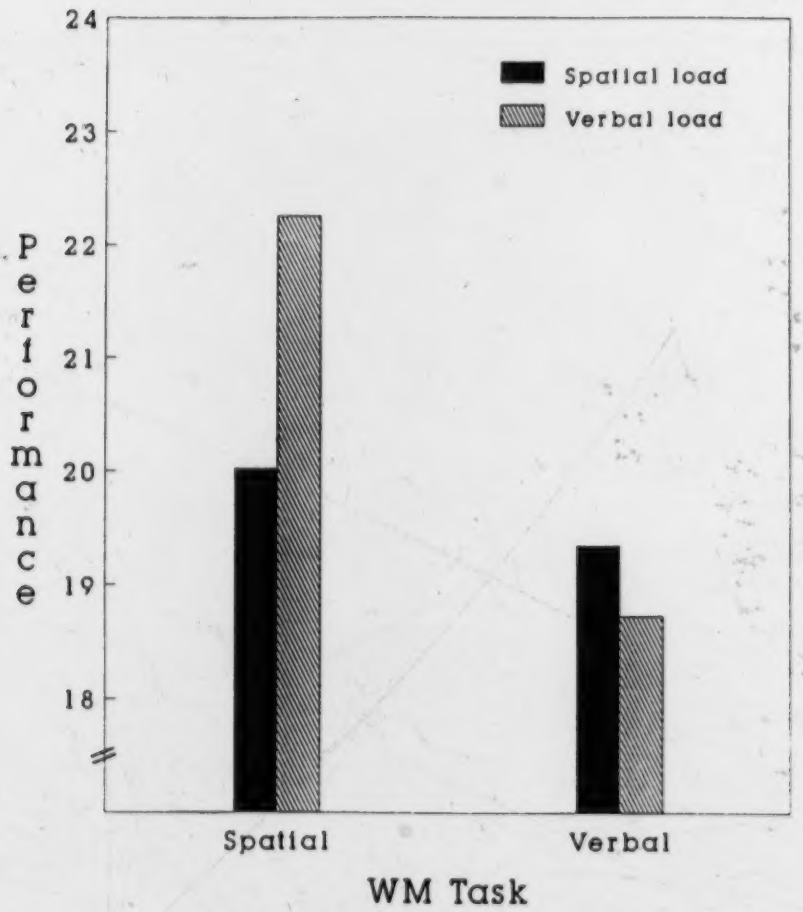

Figure 7. Expt. 2 Secondary Task Performance.

with the Spatial WM task, and that it was better when paired with a WM task of another modality. Mean scores were 21.14 and 19.03 for load tasks paired with the Spatial and Verbal WM tasks, respectively.

Spatial load task error data. The spatial secondary task data were also analyzed using the distance (cm) from responses made to the original target positions. This was done to determine whether the accuracy of responses changed as Lag number of the corresponding WM task increased. An increase in error (distance away from target) with increasing Lag would indicate that the extra storage demands of the WM task resulted in poorer storage for spatial locations in the dots task.

Using the spatial load data when paired with the Spatial WM task, a 3 (Lags 2-4) x 2 (Trial a/b) ANOVA was done using Lag and Trial as within Ss variables. Only the main effect of Trial was reliable, $F(1, 42) = 6.69$, $p < 0.013$, indicating that distance errors on the spatial load task were greater on the second trials than on the first ones at each Lag condition. Mean scores collapsed across Lag were 7.72 and 8.89 for Trials A and B, respectively. The same 2 x 2 analysis was done using the spatial load data when the task was paired with the Verbal WM task. Again, a main effect of Trial was found, $F(1, 46) = 4.37$, $p < 0.042$, indicating that error on the spatial load task was greater on the second trials than on the first trials at each Lag

condition. Mean scores collapsed across Lag were 7.96 and 8.83 for Trials A and B, respectively.

Another approach to analyzing the spatial load data was taken to investigate whether the location of the targets had an effect on the size of the distance errors. One hypothesis about spatial memory is that errors should be smaller for targets that are close to an edge because the edges can serve as landmarks or constraining boundaries (Cheng, 1990).

To assess whether subjects used the edges of each page as landmarks in order to place their responses, mean errors from targets and the distance between targets and their nearest edge were correlated. Data were included for both SWM and VWM conditions. The results indicate a weak relationship between spatial accuracy and proximity to the nearest edge ($r = 0.011$). Visual inspection of the plot of distance from edge against mean error suggests that variability of error actually *decreased* as distance from the edge increased, contrary to the prediction made. A similar plot of the data per subject also does not appear to be correlated, suggesting that subjects did not consistently use the edges as landmarks.

Discussion

Single task performance in this experiment replicated that of Experiment 1. Although a main effect of Task was found in the single task

analyses, post-hoc comparisons yielded no significant differences between tasks. Of greater interest, however, is whether selective interference effects were present. The analysis of the Spatial and Verbal WM conditions in combination provided no support for the selective interference prediction. The effect of Modality here indicates that interference effects were not present in the Spatial WM conditions, and were only marginal in the Verbal WM conditions.

The separate analyses performed on the verbal and spatial conditions support this Modality effect. A weak selective interference result was found in the Verbal WM difference data analyses. Although only marginally significant, the direction of the Match effect suggests that Ss performed more poorly when given the verbal load than when given the spatial load in conjunction with the Verbal WM task. The Spatial WM data provide scant evidence for the interference hypothesis. No clear indication of selective interference was present in either the raw score or the difference score analyses. In fact, the opposite pattern of results, although not significant, was found: Spatial WM performance in the single task condition was poorest, and was the best in the spatial load condition. It is not the case that single task performance was simply poorer than in Experiment 1. Comparing the mean scores across experiments shows that single task performance was almost the

same (M scores for Lags 2, 3, and 4 were: 8.30, 7.37, 5.63 in Expt. 1; 8.53, 6.38, 5.72 in Expt. 2) thus indicating that WM scores during the dual task conditions were unexpectedly higher than average single task performance.

Another possible explanation for the reversal of Condition effects in the Spatial WM data is that the order of tasks caused an improvement in performance on the secondary tasks. However, Order x Condition effects were not found when Order was used as a factor, so a learning effect is an unlikely explanation for the reversal.

Rather than focusing on the non-significant reversal in the Spatial WM data, it is more useful to question the *lack* of a selective interference effect. It is possible that the Spatial WM task was so absorbing that it precluded concurrent rehearsal, resulting in savings from LTM rather than from maintenance rehearsal. If this were the case, then the secondary tasks should not affect WM performance considerably, as was found, because the two tasks were done sequentially rather than concurrently.

The analysis of distance data in the Spatial secondary task indicates that the increase in memory load from the WM Lag manipulation did not affect the accuracy of the Spatial secondary task responses, further suggesting that the two tasks were done sequentially rather than concurrently.

Analysis of the secondary task data indicates that performance was greater in the match conditions than in the mismatch conditions. The source of this effect of Match is most likely due to the large difference in secondary task performance in the Spatial WM conditions. It is interesting to note that despite the absence of selective interference effects in the Spatial WM data, secondary task performance was greatly affected in these conditions. This pattern suggests that subjects were performing the primary and secondary tasks sequentially such that the load tasks did not significantly affect Spatial WM performance, but the Spatial WM task exerted modality-specific effects on the two secondary tasks.

Another possible reason for the minimal interference effects is that the secondary task storage requirements were too low. A three-item pre-load may have demanded too little storage capacity to have any interfering effects on the WM tasks. Moreover, it is possible that subjects were able to chunk the three items, consequently reducing the storage requirements of the secondary tasks.

In summary, the addition of secondary load tasks to the Verbal WM task resulted in very weak selective interference effects, but did not when using the Spatial WM task. Baddeley (1986) has discussed the potential problems associated with using a pre-load technique such as that used in the present experiment, and has suggested using an overt rehearsal task such as

articulatory rehearsal to ensure concurrent task activity. However, at present, it is not clear how to devise an overt rehearsal activity for the spatial load task, nor is it clear how subjects would be able to complete both single and dual tasks concurrently. It is too early to conclude that the WM tasks are impervious to secondary memory load interference without further research. In future, selective interference effects may be achieved using the two WM tasks if the secondary storage demands increase or if a concurrent storage task arrangement is devised.

Experiment 3

The goal of the third experiment was to determine whether the effects of adding a secondary CE task would be modality specific. The same concurrent task arrangement as in Experiment 2 was used. Rather than taxing the storage components as in Experiment 2, the secondary tasks were designed to tax CE capacity by minimizing the storage demands and requiring relatively simple and well-integrated processing routines. Subjects made left-right decisions and odd-even decisions about aspects of the WM tasks while they were performing the WM tasks.

It was expected that interference due to secondary task requirements would not be modality specific if the secondary tasks indeed tax a common CE. Furthermore, the two secondary tasks should not differ in the amount of

interference across lag conditions if the same amount of CE functioning is required at each lag.

Method

Subjects

Forty-four undergraduates, 17 females and 27 males, from the Department of Psychology at the University of Alberta participated in this experiment as an option for course credit (M age = 21.64, SD = 3.91). Data for participants who had experienced a head injury in the past year, or who were older than 35 years, were excluded from the analyses.

Design and procedures

A within subjects design similar to that of Experiment 2 was used, with Spatial and Verbal WM tasks completely crossed with Spatial and Verbal secondary tasks. Each WM task was presented alone as a control, and paired with a spatial decision making task and a verbal decision making task. The WM tasks were presented at the same Lag conditions as in the second experiment.

Because of the concurrent nature of the dual task conditions, slight changes were made across conditions to avoid conflicts in the modes of responding. While doing the Verbal WM task, subjects made button press responses to both the secondary tasks; while doing the Spatial WM task,

subjects articulated their responses for both the secondary tasks. However, the two secondary tasks are presumed to assess processing of spatial and verbal information, although the mode of responding was varied. The Verbal secondary task involved making a category decision about whether the digits presented in the WM tasks were odd or even numbers. The Spatial secondary task involved indicating whether the WM stimuli were presented in the left or right side. The secondary tasks were labelled in terms of the processing involved in each case, rather than in terms of the mode of output. The following descriptions should make this clear.

Verbal WM Conditions. In addition to performing the Verbal WM task as in the previous experiments, for the verbal secondary task, subjects concurrently indicated whether each digit heard was odd or even by making a two-choice button press response. Subjects made button press responses for every digit presented, so 12 were made at Lag 2, 13 were made at Lag 3, and so on. Odd-even responses were recorded by the computer while the experimenter recorded the Verbal WM task responses.

While doing the Verbal WM task in the spatial secondary task condition, subjects made two-choice button press responses to indicate whether digits were presented from the left or right, while concurrently saying back the numbers at the appropriate times for the WM task. A special version of the

Verbal WM stimuli were recorded so that the digits were spoken into one microphone or the other in a non-systematic fashion. In this way, subjects perceived that the digits were presented from their left or right. The button on the left side was always used to indicate a "left" response, and the button on the right, to indicate "right". Subjects made button press responses for every digit that was presented. Button presses were recorded by the computer while the experimenter recorded the Verbal WM responses.

Spatial WM Conditions. In both of the Spatial WM conditions, subjects performed the WM task as before, but slightly different stimuli were presented within the squares. For the verbal secondary task condition, digits were presented within the squares instead of "Xs". Subjects said out loud whether the digit seen was odd or even as each item was presented, while making the appropriate touch responses at Lags 2, 3, and 4. Secondary task responses were made for every digit that was presented. Stimulus duration and ISI were the same as in the basic SWM task. The experimenter recorded the odd-even responses while the SWM data were recorded by the computer.

For the spatial secondary task, smaller "Xs" appeared either in the left or right half of each square rather than in the centre. Subjects said out loud whether the "Xs" appeared inside the left or the right half of each square while concurrently performing the SWM task. Left-right responses were made for

every "X" presented, and were recorded by the experimenter.

For all of the dual task conditions, subjects were instructed to emphasize both primary and secondary tasks, but to try hard to complete their responses on the secondary tasks (see Appendix 4 for experiment briefing and instructions).

Results

In this experiment, the main question of interest is whether the addition of secondary tasks designed to tax CE capacity would cause selective interference on the WM tasks. It was expected that the size of the interference effects would not be dependent on the match or mismatch of task modalities, thus supporting the notion of a singular controller of processing.

Spatial and Verbal WM alone conditions

To determine whether performance on the WM tasks alone was similar to that of the previous two experiments, a 2 (m/f) x 2 (Spatial / Verbal WM task) x 3 (Lags 2-4) MANOVA was performed, using Sex as a between Ss variable, and Condition and Lag as within Ss variables. The main effect of Lag, $F(2,41) = 20.77$, $p < 0.001$, was reliable. Mean scores collapsed across Condition were 8.90, 8.01, and 6.52 for Lags 2-4, respectively. Newman Keuls analyses indicate that mean scores at all three Lag conditions were significantly different ($p < 0.05$).

Spatial and Verbal WM difference data combined

To answer the primary question of interest in this experiment, the difference scores were used in a combined analysis of both the Spatial and Verbal WM data. A 2 (m/f) x 2 (modality matched / mismatched) x 2 (WM modality) x 3 (Lags 2-4) MANOVA was performed with Sex as a between Ss variable, and Match, Modality and Lag as within Ss variables. A reliable effect of Match was found, $F(1,42) = 17.16$, $p < 0.001$, indicating that interference effects in the matched conditions were greater than in the mismatched conditions. Mean scores for the matched and mismatched conditions were -2.95 and -2.09, respectively. Subsequent analyses were done to investigate interference effects in each of the two WM tasks individually. The secondary task data were then analyzed to determine how performance on the decision tasks was affected by the task manipulations.

Verbal WM conditions

To determine whether interference effects occurred within the Verbal WM task conditions, a 2 (m/f) x 3 (VWM alone, VWM-verbal decision, VWM-spatial decision) x 3 (Lags 2, 3, 4) MANOVA was done with Sex as a between Ss variable and Condition and Lag as within Ss variables. Significant main effects of Condition, $F(2,41) = 79.49$, $p < 0.001$, and Lag, $F(2,41) = 21.99$, $p < 0.001$, were found. Mean scores were 7.71, 5.31 and 4.56 for

the alone, spatial and verbal decision conditions, respectively. Mean scores collapsed across Condition were 6.55, 5.89, and 5.12 for Lags 2-4, respectively. Newman Keuls analyses revealed that performance in the alone condition was greater than that of the dual task conditions ($p < 0.05$). It was also found that performance at Lags 2 and 3 was reliably greater than at Lag 4 ($p < 0.05$). Figure 8 shows mean performance for the three Verbal WM conditions as a function of Lag.

To assess interference effects on a per subject basis, a similar analysis was performed with the Verbal WM data using the difference of single and dual task conditions as the dependent measures (dual task - single task scores). A 2 (m/f) x 2 (modality match / mismatch) x 3 (Lag 2-4) MANOVA was done using Sex as a between Ss variable and Match and Lag as within Ss variables. Main effects of Match, $F(1,42) = 10.79$, $p < 0.002$, and Lag were reliable, $F(2,41) = 3.29$, $p < 0.047$, indicating that performance on the VWM task was poorer when coupled with the verbal secondary task. Mean difference scores when collapsed across Lag were -3.17 and -2.40 for the match and mismatch conditions, respectively. Mean difference scores for Lags 2-4 were -3.13, -3.03, and -2.21 respectively. Newman Keuls analyses reveal that the mean differences were not significantly different at an alpha of 0.05.

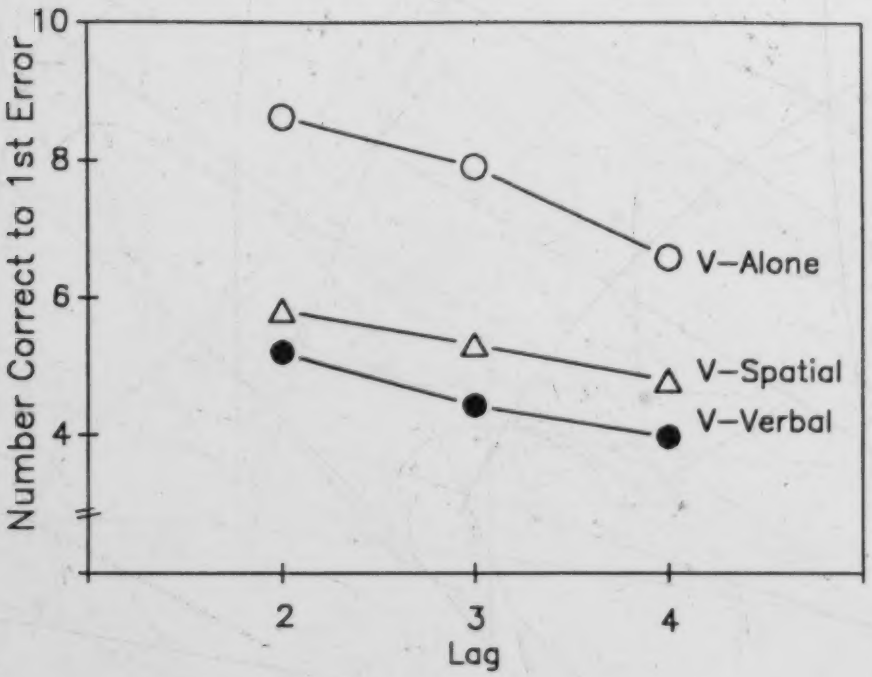

Figure 8. Expt. 3 Verbal WM Task: Alone, With Spatial and Verbal Load.

Spatial WM task conditions

To determine whether interference effects occurred within the Spatial WM task conditions, A 2 (m/f) x 3 (SWM alone, SWM-verbal decision, SWM-spatial decision) x 3 (Lags 2-4) MANOVA was done using Sex as a between Ss variable, and Condition and Lag as within Ss variables. Main effects of Condition, $F(2,41) = 22.48$, $p < 0.001$, and Lag, $F(2,41) = 30.87$, $p < 0.001$, were reliable. Mean scores were 7.91, 6.13, and 5.18 for the alone, verbal and spatial decision conditions, respectively. Mean scores collapsed across Condition were 7.52, 6.81, and 4.89 for Lags 2-4, respectively. Newman Keuls analysis revealed that performance on the Spatial WM task alone condition was greater than that of the two dual task conditions ($p < 0.01$). Also, performance on Lags 2 and 3 was significantly greater than that of Lag 4 ($p < 0.01$). Figure 9 shows mean Spatial WM performance in the three conditions.

To assess interference effects on a per subject basis, a similar analysis was performed using difference scores (dual task scores - single task scores) for each subject. A 2 (m/f) x 2 (modality match / mismatch) x 3 (Lag 2-4) MANOVA was done using Sex as a between Ss variable and Match and Lag as within Ss variables. A reliable effect of Match was found, $F(1,42) = 5.65$, $p < 0.022$, indicating that performance on the SWM task was poorer when

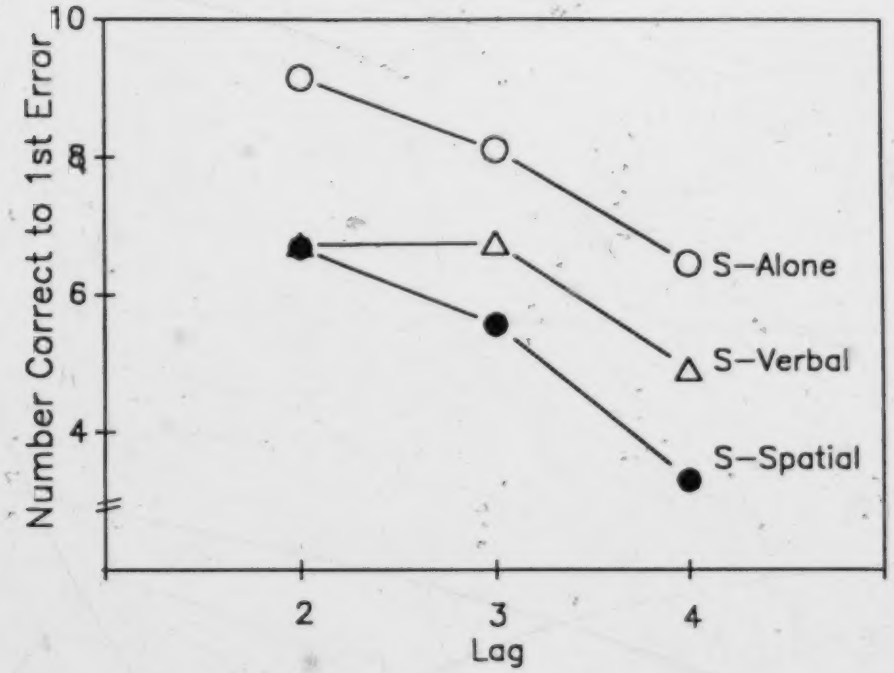

Figure 9. Expt. 3 Spatial WM Task: Alone, With Spatial and Verbal Load.

coupled with the spatial secondary task. Mean difference scores collapsed across Lag were -2.73 and -1.78 in the match and mismatch conditions, respectively.

Secondary tasks

To examine whether the type of WM task affected secondary task performance, the secondary task data were converted to percentages to make them comparable across lags. In addition, the first two, three and four items were omitted from the scores in Lag 2-4, respectively, to correct for the lead-in items in which subjects were performing the secondary tasks only. A 2 (WM modality) x 2 (match / mismatched) x 3 (Lags 2-4) MANOVA was done using Modality, Match and Lag as within Ss variables. The main effects of Modality of WM task, $F(1,39) = 11.52$, $p < 0.002$, and Match, $F(1,39) = 11.45$, $p < 0.002$, were reliable. These effects indicate that overall secondary task performance was greater when paired with the Spatial WM task, and was greater in the mismatched conditions. The Lag effect was also reliable, $F(2,38) = 12.53$, $p < 0.001$. Post-hoc contrasts indicate that performance at Lag 2 was significantly poorer than at Lags 3 and 4 ($p < 0.01$). Figure 10 shows mean secondary task performance as a function of Lag.

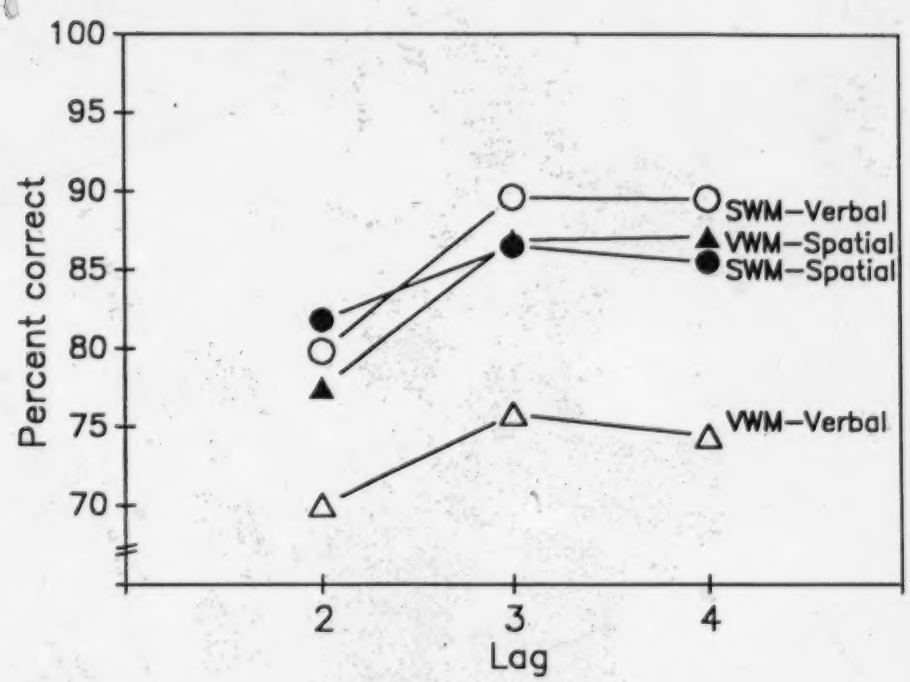

Figure 10. Expt. 3 Secondary Task Performance by Lag.

Relation among primary and secondary tasks

Pearson r correlations between the WM task scores and their corresponding secondary task scores in the dual task conditions were obtained to further investigate the possibility of performance tradeoffs (see Table 2 for correlations). Although the correlations were not significant, the trend shown within each dual task condition is that the strength of the correlations decreases with increasing lag number, indicating that primary and secondary task tradeoffs are not prominent.

Discussion

The results of the single task analyses replicate those of the first two experiments, indicating that there were no overall differences between Spatial and Verbal WM task performance. Of greater interest, however, is whether the secondary tasks resulted in modality-specific interference effects. When the secondary tasks required processing concurrently with the WM tasks, clear selective interference effects were present in both modalities in varying degrees.

The analysis of the difference data for the Spatial and Verbal WM tasks in combination indicates that task interference was greater when primary and secondary task modalities were matched, as evidenced by a main effect of Match. The individual analyses of the difference scores also indicate a

Table 2
Pearson R Correlations Between Expt. 3 WM and Secondary Task Performance

	Lag		
Secondary Task	2	3	4
Spatial WM Task			
Spatial Decision	0.363	0.296	0.243
Verbal Decision	0.279	0.260	-0.020
Verbal WM Task			
Spatial Decision	0.327	0.172	0.134
Verbal Decision	0.270	0.135	0.252

* $p < 0.05$
** $p < 0.01$

selective interference effect: both the Verbal and Spatial WM analyses yielded a significant effect of Match, such that relative to single task performance, WM scores were lower in the conditions in which primary and secondary tasks were matched in modality. Also notable is the lack of reliable Lag effects in the difference data analyses, suggesting that interference effects did not increase as storage requirements in the WM tasks increased. To the extent that the secondary tasks assessed CE ability, this finding supports the assumption that the CE requirements in the WM tasks remain constant as Lag number increases.

The results of the individual raw data analyses also support the selective interference finding. In both the Spatial and Verbal WM conditions, performance was best in the single task trials, followed by the mismatched task trials (SWM-verbal decision, VWM-spatial decision), and worst in the matched trials (SWM-spatial decision, VWM-verbal decision).

Because of the clear interference effects found, it is appropriate to ask whether tradeoffs occurred between primary and secondary tasks. Secondary task analyses indicate that performance on the decision tasks increased with Lag number, despite correcting for the lead-in items in which subjects were not making responses to both tasks concurrently. This increasing pattern occurred most likely because subjects failed on the WM task and continued

doing the secondary tasks, consequently inflating their secondary task scores. Therefore it is unlikely that the increase in secondary task performance coupled with a decrease in WM task performance across Lag conditions signifies true performance tradeoffs. It is also doubtful that dual task tradeoffs occurred to a great extent if one considers that the correlations between primary and secondary task measures were non-significant (see Table 2).

Taken together, the results of Experiment 3 indicate that there are strong modality-specific effects produced by secondary tasks designed to tax CE capacity. These results support Daneman and Tardif's (1987) hypothesis that there are specialized executive components for different modalities or processing domains, and that processing and the control of processing are part of the same capacity limited component. However, the results equally support the hypothesis that there are modality-specific processing and storage components but a single CE component for the control of processing, if one distinguishes between capacity for processing and capacity for the control of processing. The secondary tasks used in this experiment undoubtedly require some processing of spatial and category information in addition to requiring the control aspects of the CE. Until a paradigm is devised to isolate processing from control functions, the issue of single or multiple CE components remains unresolved.

General Discussion

Are the Spatial and Verbal WM tasks comparable?

Findings from the three experiments suggest that the Spatial WM task developed does result in performance similar to that of the Verbal WM task. Analyses of the Spatial non-target WM task indicate that the fidelity of the memory trace for spatial locations diminishes as memory load (Lag number) increases and as subjects progress in each sequence, as if the location memory for previous items interferes with their ability to respond as accurately as before.

When the Spatial and Spatial non-target WM tasks are compared, one can conclude that the squares on the screen provided substantial aid in locating the correct spatial locations to be touched, as reflected by lower scores in the Non-target conditions. It may be more plausible to refer to the Non-target version as a more specific "spatial" task because of the lack of on-screen cues. However, one could argue that because the digits one through nine are so readily available to the subject, the target-present version of the Spatial WM task is more comparable to the verbal task. At present, one can conclude that when the same criteria are used to score the WM tasks, the target-present version of the Spatial WM task and the Verbal WM task show similar performance functions.

Two independent storage components?

Results from the second experiment lend minimal support to the hypothesis of separate storage components in WM that are both limited in capacity. The results indicate that tradeoffs across tasks were not present, suggesting that the primary and secondary tasks were done sequentially rather than concurrently. At present, it is premature to conclude that selective interference effects are not possible using the two WM tasks until experiments are done to rule out some of the reasons for the present results.

There are a few possible steps to take in this regard. One approach is to increase the secondary memory load to determine whether the null results were due to the low storage requirements of the tasks in the concurrent conditions. It is possible that subjects were chunking the location of the dots or the nonsense words, and remembering them as a configuration rather than as individual items. Increasing the secondary memory load might counteract the benefits of chunking. It may be the case that the memory load tasks were simply too amenable to chunking to produce any significant interference effects.

Another possible direction is to create memory load tasks that are concurrent with the WM tasks in order to discourage subjects from doing the two tasks sequentially. Despite positive results in the literature (e.g.,

Baddeley & Hitch, 1974; Herdman & Friedman, 1985) using a memory pre-load paradigm similar to that of Experiment 2, the present findings show no evidence of selective interference. However, it is also notable that Baddeley (1986) discussed the utility of using concurrent tasks such as articulatory suppression to ensure concurrent occupation of the rehearsal mechanisms attributed to the WM system. A future challenge will be to find a concurrent memory load task that emphasizes storage and minimizes processing and control demands.

Two CE components or one?

Results from Experiment 3 support the notion of two specialized CE components. However, the data provide equal support for the idea of two specialized domains of processing.

Baddeley (1986) ascribes many control functions to the CE component, but makes little mention of processing aside from alluding to Norman and Shallice's (1986) model, in which schemas for processing routines are run off automatically once they are activated. It is not clear in Baddeley's account whether the processes and the control functions are part of the same limited capacity component or constitute two separate capacity-limited components.

Theorists have not reached an agreement on this particular issue in the WM literature. Daneman and Tardif (1987) consider the control of processing

and the cognitive processes themselves as using part of the same limited capacity component, and different processing domains as independent in capacity. A theoretical distinction can be made between the control of processing (arguably the role of the CE), and the processes themselves. It is more difficult to operationalize the distinction, however. Despite carefully designing the two secondary CE tasks to minimize processing and storage demands, the third experiment nevertheless resulted in selective interference.

Conclusions

When one considers all three experiments, one of the most striking outcomes is the consistency in WM performance across experiments. If the WM tasks indeed measure CE ability, the lack of a substantial difference between the verbal and spatial versions of the WM task, in all three experiments, supports the idea of a unitary CE component.

A second if not more striking result is the increase in magnitude of interference in Experiment 3 as compared with Experiment 2. It is evident that the concurrent CE tasks affected WM performance far more than the memory load tasks. This is not surprising if one assumes that the WM tasks themselves were designed to maximize CE control requirements. One would expect that two CE tasks performed concurrently would certainly result in task interference.

Furthermore, the null results in Experiment 2 are not surprising if one assumes that the WM tasks do not require much storage capacity, and so should not be very sensitive to additional memory loads, especially memory loads of three items at a time. Interference effects might have been stronger if the secondary tasks required memory for a greater number of items. This second overall result provides support for the previous conclusion that the WM paradigm emphasizes CE functions and demands little storage capacity until the higher Lag conditions (Dobbs & Rule, 1989).

The reported research succeeded in demonstrating several things: (1) the Spatial and Verbal WM tasks yield comparable performance across several Lag conditions (2) Spatial WM performance declined drastically when location cues (squares) were not present on the computer screen (3) concurrent decision-making tasks impaired WM performance more than memory pre-load tasks. What remains to be determined is whether it is the size of the memory load or the concurrent aspect of the secondary tasks that produced the null results in Experiment 2, and interference effects in Experiment 3.

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APPENDIX 1: Instructions for Experiment 1

Briefing

Hi. Thanks for coming in today. My name is Karen Li and I'm a graduate student in the Department of Psychology. I will be giving you six short tests, three that involve giving touch responses on this touch-sensitive screen, and three that involve repeating back numbers that you will hear. Some parts of this experiment are harder than others, so please just try to do your best. Your name will be kept confidential, as I will only be recording the ID codes that I assign for each person. Are there any questions before I begin to explain the tasks in more detail?

Task Instructions

Spatial WM task. [COND1.EXE]

In this task, you will see nine squares on the computer screen in a random arrangement. You will respond by touching the squares when you see an 'X' come on inside one of the squares. SHOW DIAGRAM It is important that when you touch the screen, you approach it directly, and after each response you take your hand completely away from the screen. (demonstrate and ask participant to do it) There will be six conditions in this task: Lag 0 to Lag 5. In the Lag 0 condition, you make a touch response to the square in which the 'X' appears immediately after it comes on. You will make ten of these responses. In the Lag 1 trial, you will be making the same type of response, but when the first 'X' comes on, don't touch it until the second 'X' appears. Then, when the third one appears, you touch the square where the second one came on. You will essentially be tracking the 'Xs' in the order that they appear, but you will track them one square back from the one you have just seen. Was that part clear? (repeat again if subject does not understand). In Lag 2 you will wait for two 'Xs' to come on before you start responding, and you will be tracking the sequence two squares back from the one you have just seen. In Lag 3, it will be three squares back, and in Lag 4, it will be four squares back (and so on for Lag 5). Do you understand?

There will be a pause after each Lag condition, so you can remind yourself about what you are supposed to do in the next Lag. If you forget, ask me and I will help you. When you are ready to continue, press the return key to start the next Lag. Remember to make 'clean' touch responses and take your hand away from the screen after each touch response. Any questions? ... OK, let's begin.

Spatial Non-target WM task. [TARGET.EXE]
This task is very similar to the first task in that you will be doing the same lag conditions with two trials per lag. However, instead of seeing squares with crosses in them, you will see a blank screen with small green dots that appear about every two seconds. So again, you will make touch responses at the appropriate times to the locations where you saw the dots appear.

Verbal WM task. [on audiotape]
In this task, you will not be using the computer screen. Instead, you will hear numbers from the tape recorder, and you will respond out loud while I write down your answers. This task is like the other lag tasks, so you will first say the number immediately after you hear it in the Lag 0 condition. Remember, in Lag 1, you will wait until you hear the second number before you respond with the first number you heard, and so on, for the other lags. Are there any questions? ... OK, let's begin.

Digit Span Forward. [presented by experimenter]
Again, you will be hearing numbers, but this time, I will be saying them, and then you will be responding out loud. I will start with a sequence of four numbers, and then I will tell you to repeat them back in the same order that you heard them. The sequences will increase in length as you progress. Are there any questions? ... OK, let's begin.

Spatial Span. [SSPAN.EXE]
In this task, you will be using the touch screen again. You will see nine squares on the screen, and in each trial, 'Xs' will come on and then disappear in a certain sequence. After the sequence has been presented, you will see the word, "RECALL" in the upper left corner of the screen, and then you will touch the squares in the same order that you saw them appear. You will start with a sequence of four 'Xs', and each time you do one correctly, the next sequence will increase by one item. If you make a mistake, you will get a second chance at the same level. Remember, it is very important that you make 'clean' touch responses and take your hand away from the screen after each response. Any questions?... OK, let's begin.

Spatial non-target span. [TSPAN.EXE]
The next task is very similar to the other span task on the computer. A series of items will be presented and then you will be instructed to recall the items in the order that you saw them. Again, the span length will increase as you

progress, and you will start each trial by touching the screen.

Debriefing

First, I would like to thank you for you effort and participation in this study. You may have noticed that all of the tasks that I had you do were very similar in that you had to retain items in memory for a short time and then output them. However, the tasks differed in that some of them contained verbal information, that is, number information, while other tasks contained only spatial, or location, information.

One goal of this study was to investigate the storage of these two different types of information in memory, and so I had you do the task in which you saw sequences of crosses come on at various locations, and then had to repeat the sequence back in the correct order. Also, that is why I had you listen to sequences of numbers and repeat them back in the correct order. These tasks are designed to test people's **spatial span** and **verbal span**, respectively. More importantly, I wanted to test your ability to hold a few items (both spatial and verbal) in storage while switching between giving responses, storing new items, and "dumping" old items from memory. This kind of switching of processes involves **working memory.**

Working memory ability is thought of as the ability to hold several items of information in storage while you manipulate those items. For example, if you are given a series of words to remember, and are asked to repeat them all back after mentally arranging them in alphabetical order, you are using working memory. In contrast, if you are only repeating the items back in the order in which they were presented, you are just using storage, and not working memory. According to the model of working memory, there is a store for verbal information, called the **articulatory loop**, and a separate store for visuo-spatial information, called the **visuo-spatial scratch pad**. In addition to these stores, there is a controlling mechanism called the **central executive** that is responsible for the control and organization of processes such as encoding information into memory, and retrieval from memory. The tasks involving lag conditions are considered working memory tasks that use the central executive to rapidly switch from one process to another, while requiring the storage of only a few items at Lag 0 and 1, and more items as the lag number increases.

What we are interested in finding out from the results is first, whether or not there is a difference in performance depending on what kind of information is available - either verbal or spatial information. Secondly, we are interested in finding out whether your span measures correspond to your performance on the working memory measures - digit span with the verbal

working memory task, and spatial span with the spatial working memory task. We expect that span performance will be more closely related to working memory performance as the lag number goes up, because the storage requirements increase as lag number increases. We are especially interested in the functioning of the central executive because it is thought that this aspect of working memory is the one that declines with age, and especially so with people who suffer from head injuries or dementia. For example, people with a specific type of dementia called Alzheimer's disease typically have problems performing tasks that use the central executive, such as doing mental arithmetic. The paper that you will be reading is about the central executive, and describes this type of decline as well as the working memory model in more detail.

If you have any questions about the study, please feel free to contact me (Karen Li) in the department. Again, thank you for your participation.

APPENDIX 2: Paralogs taken from Taylor (1959)

Numbers in parentheses indicate the number of responses in the most frequent category (real word associated). One-hundred and two Ss were used in the norming experiment. Words were presented verbally by the experimenter and repeated again, in groups of three per trial. Order of groups was counterbalanced.

Group A
Lag 2 trial 1
kalab (4) zirol (4) hakim (6)
trial 2
zumen (6) tolan (9) menad (9)

Lag 3 trial 1
yuval (9) kapox (5) hyson (6)
trial 2
yamen (5) gadid (6) tolan (9)

Lag 4 trial 1
genet (17) gojey (8) bulas (6)
trial 2
celom (6) tabor (8) gerah (9)

Group B
Lag 2 trial 1
tulak (9) jerid (9) felid (9)
trial 2
tarop (5) carom (7) jabot (7)

Lag 3 trial 1
silos (26) negus (24) farod (26)
trial 2
furan (22) goral (15) tapis (30)

Lag 4 trial 1
zonad (32) davit (33) kupod (41)
trial 2
zolar (23) vumac (34) yuror (19)

APPENDIX 3: Instructions for Experiment 2

Briefing

Hi. Thanks for coming in today. My name is _____. I will be giving you six short tests. They will be variations on two basic tasks. One involves listening to numbers through the headphones, and the other involves making touch responses to shapes that appear on the computer screen. Some parts of this experiment are harder than others, so please just try to do your best. Your name will be kept confidential, as I will only be recording the ID codes that I assign for each person. Are there any questions before I begin to explain the tasks in more detail?

Task Instructions

Spatial WM task: (ALONE)

In this task, you will see nine squares on the computer screen in a random arrangement. **SHOW DIAGRAM** You will respond by touching the squares when you see an 'X' come on inside one of the squares. It is important that when you touch the screen, you approach it directly, and after each response you take your hand completely away from the screen. **DEMONSTRATE AND ASK SUBJECT TO DO IT**

There will be three levels in this task: Lag 2 to Lag 4. The computer will present a series of 'Xs' and you will be tracking them in the correct order. In Lag 2, I would like you to watch for the first two Xs to come on, and when you see the third X, touch the square where you saw the first one come on. When you see the 4th X come on, I would like you to touch where you saw the 2nd X come on. When you see the 5th X come on, I would like you to touch where you saw the 3rd X come on. And so on. You will make a total of ten of these responses. In Lag 3, you will be making the same type of response, but now you will be tracking the items THREE behind instead of two. And for Lag 4, you will be doing the same thing, but you will wait until four items go by before you start tracking the Xs FOUR items back in the sequence. Was that part clear? **SHOW THE VERBAL WM SCORE SHEET TO EXPLAIN THE WAITING CONCEPT IF IT IS NOT CLEAR**

It is important to remember that you have to respond fairly soon after you see an X come on. The program is paced at about 2 seconds between each X presentation, so try to pace your responses accordingly. If you feel like you have lost track, try your best to get back into the task and finish up the trial. Also, there will be a pause after each Lag condition, so you can remind yourself about what you are supposed to do in the next Lag. If you forget, ask me and I will help you. When you are ready to continue, hit the return

key to start the next Lag. Remember to make 'clean' touch responses and take your hand away from the screen after each touch response. Any questions? ... OK, let's begin.

Verbal WM task: (ALONE)
In this task you will be hearing numbers presented at about one every 2 seconds, and I would like you to repeat them back to me at the appropriate times. There are three conditions to the task: Lag 2, 3, and 4. In Lag 2, I would like you to listen for the first two numbers and remember them, but don't repeat them. When you hear the 3rd number, I'd like you to say the first number that you heard. When you hear the 4th number, I'd like you to say the 2nd number that you heard. When you hear the 5th number, say the 3rd number, and so on. Remember that you have to keep up with the pace of the task. In Lag 3, you will again be tracking numbers, but you will wait until the first THREE digits go by before you start to track them, starting with the first item. In Lag 4, you will be tracking numbers, but you will always be four items behind in the sequence.

Remember, try to keep up with the pace of the task, and if you feel like you have lost track of the sequence, try your best to get back into it. There will be a pause in the tape between each trial, when I will be announcing the lag number coming up in the next trial. You can ask me to stop the tape if you want me to remind you of how to do the next lag number. Any questions? ... Ok, let's begin.

Spatial WM task with spatial load:

Now we will be doing the spatial WM task again, but this time, with an additional task before and after each trial. You will be getting two trials of Lags 2, 3, and 4 again, but before each trial, I will show you a series of three dots. Remember the location of these dots as accurately as possible. After a WM trial, I will ask you to reconstruct the three dots by drawing Xs in the correct locations. I would like you to label each X to indicate the order of the three dots. So you want to be as accurate as possible with both location and order information. Is this part clear?

It is EXTREMELY important that you do well on the memory load task. Points will be allotted for each correct response that you make, so please try very hard to remember the three items at the beginning of each trial.

Spatial WM task with verbal load:

Now we will be doing the spatial WM task, but with an additional

verbal memory load. You will be doing two trials each of Lags 2, 3, and 4, but before each trial, I will be saying three nonsense words that you will have to remember. After each trial, I will ask you to say back the three words in the correct order. Try to repeat them as accurately as possible, and in the same order as I presented them to you. Is this part clear?

It is EXTREMELY important that you do well on the memory load task. Points will be allotted for each correct response that you make, so please try very hard to remember the three items at the beginning of each trial.

Verbal WM task with verbal load:

Now you will be doing the verbal WM task with two trials each of Lags 2, 3, and 4. However, before each trial, I will be saying three nonsense words that I'd like you to remember. After each trial, I will ask you to say back the three words in the correct order. Try to repeat them as accurately as possible, and in the same order as I presented them to you. Is this part clear?

It is EXTREMELY important that you do well on the memory load task. Points will be allotted for each correct response that you make, so please try very hard to remember the three items at the beginning of each trial.

Verbal WM task with spatial load:

Now you will be doing the verbal WM task again, with two trials each of Lags 2, 3, and 4. Before each trial, I will be showing you a series of three dots to remember. After each trial, I will ask you to reproduce the three dots by drawing an X in each of the locations, and labelling them A, B, AND C, to indicate the order that they were presented. Remember to be as accurate as you can because both location and order information is important. Is this part clear?

It is EXTREMELY important that you do well on the memory load task. Points will be allotted for each correct response that you make, so please try very hard to remember the three items at the beginning of each trial.

Debriefing

First, I would like to thank you for you effort and participation in this study. You may have noticed that all of the tasks that I had you do were very similar in that you had to retain items in memory for a short time and then output them. However, the tasks differed in that some of them contained verbal information, that is, number information, while other tasks contained only spatial, or location, information.

One goal of this study was to investigate the storage of these two different types of information in memory, and so I had you do the task in

which you saw sequences of crosses come on at various locations, and then had to repeat the sequence back at the appropriate times. Also, that is why I had you listen to sequences of numbers and repeat them back at the appropriate times. These tasks are designed to test people's **spatial working memory** and **verbal working memory**, respectively. More importantly, I wanted to test your ability to hold a few items (both spatial and verbal) in storage while switching between giving responses, storing new items, and "dumping" old items from memory. This kind of switching of processes involves **working memory.**

Working memory ability is thought of as the ability to hold several items of information in storage while you manipulate those items. For example, if you are given a series of words to remember, and are asked to repeat them all back after mentally arranging them in alphabetical order, you are using working memory. In contrast, if you are only repeating the items back in the order in which they were presented, you are just using storage, and not working memory. According to the model of working memory, there is a store for verbal information, called the **articulatory loop**, and a separate store for visuo-spatial information, called the **visuo-spatial scratch pad**. In addition to these stores, there is a controlling mechanism called the **central executive** that is responsible for the control and organization of processes such as encoding information into memory, and retrieval from memory. The working memory tasks that you did use the central executive to rapidly switch from one process to another, while requiring the storage of only a few items at Lag 2, and more items as the lag number increases.

What we are interested in finding out from the results is first, whether or not there is a difference in performance depending on what kind of information is available - either verbal or spatial information. Secondly, we are interested in finding out whether your performance on the working memory measures got worse when an additional memory load was given. We manipulated the modality of the secondary memory load by varying whether spatial load was paired with the spatial WM task, and whether verbal load was paired with verbal WM task.

We expect that memory load will be more detrimental to working memory performance as the lag number goes up, because the storage requirements increase as lag number increases. More importantly, we expect that working memory performance will be hurt more when the modality of the secondary memory load task is the same as the modality of the working memory task. We are especially interested in the functioning of the central executive because it is thought that this aspect of working memory is the one

that declines with age, and especially so with people who suffer from head injuries or dementia. For example, people with a specific type of dementia called Alzheimer's disease typically have problems performing tasks that use the central executive, such as doing mental arithmetic. The paper that you will be reading is about the central executive, and describes this type of decline as well as the working memory model in more detail.

If you have any questions about the study, please feel free to contact me (Karen Li) in the department. Again, thank you for your participation.

APPENDIX 4: Instructions for Experiment 3

Briefing

Hi. Thanks for coming in today. My name is _____. They will be variations on two basic tasks. One involves listening to numbers through the headphones, and the other involves making touch responses to shapes that appear on the computer screen. Some parts of this experiment are harder than others, so please just try to do your best. Your name will be kept confidential, as I will only be recording the ID codes that I assign for each person. Are there any questions before I begin to explain the tasks in more detail?

Task Instructions

Spatial WM task: (ALONE)

In this task, you will see nine squares on the computer screen in a random arrangement. **SHOW DIAGRAM** You will respond by touching the squares when you see an 'X' come on inside one of the squares. It is important that when you touch the screen, you approach it directly, and after each response you take your hand completely away from the screen. **DEMONSTRATE AND ASK SUBJECT TO DO IT**

There will be three levels in this task: Lag 2 to Lag 4. The computer will present a series of 'Xs' and you will be tracking them in the correct order. In Lag 2, I would like you to watch for the first two Xs to come on, and when you see the third X, touch the square where you saw the first one come on. When you see the 4th X come on, I would like you to touch where you saw the 2nd X come on. When you see the 5th X come on, I would like you to touch where you saw the 3rd X come on. And so on. You will make a total of ten of these responses. In Lag 3, you will be making the same type of response, but now you will be tracking the items THREE behind instead of two. And for Lag 4, you will be doing the same thing, but you will wait until four items go by before you start tracking the Xs FOUR items back in the sequence. Was that part clear? **SHOW THE VERBAL WM SCORE SHEET TO EXPLAIN THE WAITING CONCEPT IF IT IS NOT CLEAR**

It is important to remember that you have to respond fairly soon after you see an X come on. The program is paced at about 2 seconds between each X presentation, so try to pace your responses accordingly. If you feel like you've lost track, try your best to get back into the task and finish up the trial. Also, there will be a pause after each Lag condition, so you can remind yourself about what you are supposed to do in the next Lag. If you forget, ask me and I will help you. When you are ready to continue, hit the return key to start the next Lag. Remember to make 'clean' touch responses and take

your hand away from the screen after each touch response. Any questions? ... OK, let's begin.

Verbal WM task: (ALONE)
In this task you will be hearing numbers presented at about one every 2 seconds, and I would like you to repeat them back to me at the appropriate times. There are three conditions to the task: Lag 2, 3, and 4. In Lag 2, I would like you to listen for the first two numbers and remember them, but don't repeat them. When you hear the 3rd number, I'd like you to say the first number that you heard. When you hear the 4th number, I'd like you to say the 2nd number that you heard. When you hear the 5th number, say the 3rd number, and so on. Remember that you have to keep up with the pace of the task. In Lag 3, you will again be tracking numbers, but you will wait until the first THREE digits go by before you start to track them, starting with the first item. In Lag 4, you will be tracking numbers, but you will always be four items behind in the sequence.

Remember, try to keep up with the pace of the task, and if you feel like you have lost track of the sequence, try your best to get back into it. There will be a pause in the tape between each trial, when I will be announcing the lag number coming up in the next trial. You can ask me to stop the tape if you want me to remind you of how to do the next lag number. Any questions? ... Ok, let's begin.

Spatial WM task with left-right decision:

Now we will be doing the spatial WM task again, but this time, with an additional twist. You will be getting two trials of Lags 2, 3, and 4 again. However, this time you will see the Xs appearing in either the left or right hand side of the squares. While you do the WM task as before, I would like you to say out loud, whether the X's appear on the left or right of the squares.
SHOW ON DIAGRAM
It is important that you make a left-right decision for EACH X that is presented. That means that you will be giving responses to the lead-in items even before you start to make touch responses. Both tasks are equally important, and even if you have lost track of one part of the task, try to continue with the other part. Is this clear?

Spatial WM task with odd-even decision:

Now we will be doing the spatial WM task, but with an additional

twist. You will be doing two trials each of Lags 2, 3, and 4. However, instead of seeing Xs like before, you will be seeing digits appear in each of the squares. I'd like you to decide whether the numbers are odd or even and say your answer immediately after the number is presented. Is this part clear? This means that you will get started on the odd-even decision component before you start to make touch responses. You will make odd-even responses for EVERY item that is presented. Both tasks are equally important, and even if you have lost track of one part of the task, try to continue with the other part. Is this clear?

Verbal WM task with odd-even decision:

Now you will be doing the verbal WM task with two trials each of Lags 2, 3, and 4. While you are doing the verbal WM task, I would like you to make an odd-even decision on each of the numbers presented. That is, when you hear a number, I'd like you to decide whether it is odd or even and press the appropriate button SHOW BUTTONS So while you are doing the WM task as before, I would like you to do this additional task. Is this part clear? I'd like you to make your odd-even responses immediately after each number is presented, so that you can keep up with the task. Both parts are equally important. If you lose track of one part of the task, try to continue with the other part. Is this clear?

Verbal WM task with left-right decision:

Now you will be doing the verbal WM task again, with two trials each of Lags 2, 3, and 4. This time, the numbers will be presented to you in randomly alternating channels. While you do the WM task, as before, I'd like you to indicate whether the number that you just heard came from the left or the right channel of the headphones. You will do this by pressing the appropriate buttons. SHOW BUTTON APPARATUS. This means that you will be making a response to the left-right decision after you hear EVERY number. Try to do this immediately and keep up with the tape. Both parts are equally important, but if you lose track of one part of the task, try to continue with the other part. Is this clear?

Debriefing

First, I would like to thank you for you effort and participation in this study. You may have noticed that all of the tasks that I had you do were very similar in that you had to retain items in memory for a short time and then output them. However, the tasks differed in that some of them contained verbal information, that is, number information, while other tasks contained

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What we are interested in finding out from the results is first, whether or not there is a difference in performance depending on what kind of information is available - either verbal or spatial information. Secondly, we are interested in finding out whether your performance on the working memory measures got worse when an additional task was given. We manipulated the modality of the secondary task by varying whether spatial decisions (left-right) were paired with the spatial WM task, and whether verbal decisions (odd-even) were paired with verbal WM task.

It is to be determined whether working memory performance will be hurt more when the modality of the secondary task is the same as the modality of the working memory task. We are especially interested in the functioning of the central executive because it is thought that this aspect of working memory is the one that declines with age, and especially so with people who

suffer from head injuries or dementia. For example, people with a specific type of dementia called Alzheimer's disease typically have problems performing tasks that use the central executive, such as doing mental arithmetic. The paper that you will be reading is about the central executive, and describes this type of decline as well as the working memory model in more detail.

If you have any questions about the study, please feel free to contact me (Karen Li) in the department. Again, thank you for your participation.